

Frozen motion model and dilepton production from 200A GeV S+W collisions at CERN SPS

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We have analysed the invariant mass distribution of dileptons in S+W collisions at 200A GeV as measured by the HELIOS-3 collaboration at CERN SPS. Three scenarios were considered where the collision lead to formation of (i) the quark-gluon plasma, (ii) the ideal hot hadron gas and (iii) the viscous hot hadron gas. The space-time evolution was governed by the minimal extension of the Bjorken hydrodynamics. All the three scenarios indicate excess dileptons in the experiment.

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I. INTRODUCTION

In relativistic heavy ion collisions, the deconfined state of quarks and gluons (QGP) is expected to be produced. Lattice QCD calculations also predict the formation of QGP. However, until now there is no conclusive proof that QGP is formed in heavy ion collisions. It is then essential to consider the possibility of formation of hot hadronic gas also. The major aim of the present day relativistic heavy ion experiments is to identify which one of these two possible states is produced as the initial state. Dileptons due their weak final state interaction are considered to be ideal probe for investigating the initial state of the fireball. Several groups have measured the invariant mass distributions of dileptons at CERN. Two muon experiments HELIOS-3/NA34 [1] and NA38 [2] have measured dimuons in central S+W collisions in the forward rapidity region. They observed unaccounted excess of dileptons. Excess dileptons were also reported by the CERES collaboration [3–5], who have measured low invariant mass dileptons in the central rapidity region, in central collisions of S+Au. Shuryak and Xiong [6] have analysed the invariant mass distribution of dileptons as obtained by the NA34 and NA38 collaboration. They assumed that after the collision a mixed phase is produced. They found that in the invariant mass region 1-2 GeV, the model do not produce sufficient lepton pairs to explain the experiments. They argued that the conventional model of expansion can not explain the excess dileptons and proposed a slow expansion model where the mixed phase fireball expands slowly, during the time period of 30-40 fm. Recently Srivastava et al [7] analysed the CERES as well as the HELIOS-3 dilepton production data. The CERES data corresponds to central rapidity range and was analysed using the Bjorken hydrodynamics. Bjorken hydrodynamics could not be used for the HELIOS-3 data as it lies in the forwards rapidity region. They followed the treatment of Sinyukov et al [9] and retained the distinction between the fluid and particle rapidities, with fluid rapidities limited between $[-1.7, 1.7]$. They considered two scenarios, one with the phase transition to the QGP, the other without the phase transition. It was found that the CERES data which covered invariant mass range 0.2-1.5 GeV is well explained in both the scenario's. However, the HELIOS-3 data could be explained only in the scenario with the phase transition. The scenario without the phase transition overpredict the large invariant mass data by a factor of ~ 40 .

In the present paper, we have analysed the HELIOS-3 dilepton mass distribution in the frozen motion model [6]. The purpose was to see whether in a different model same conclusion (i.e. the data favor QGP) can be obtained. The frozen motion model [6] is the minimal extension of Bjorken hydrodynamics and do not demand plateau in the rapidity distribution. It is appropriate for the HELIOS-3 data which covers the forward rapidity region, where the rapidity distribution do not exhibit plateau. As in ref. [7] two possible scenario's which can arise after the collision have been considered namely the phase transition (PT) scenario where QGP is formed in the initial state, and the no phase transition (NPT) scenario, where ideal hot hadronic gas is formed. In addition, we have considered a scenario where viscous hadronic gas is formed in the initial state. Recently we have shown that formation of hot viscous hadronic gas can explain the WA80 [10] preliminary single photon data for 200 AGeV S+Au collisions reasonably well [11]. It also describe the p_T distribution of neutral pions as obtained by the WA80 collaboration [12]. We do not reanalyse the CERES data as we are interested to see whether the dilepton data are sensitive enough to discriminate between the different scenario's considered. The analysis of Srivastava et al [7] revealed that the CERES data are not sensitive to the precise nature of initial state due to low invariant mass coverage. Also, in the central rapidity region, frozen motion model is equivalent to the Bjorken model. As the CERES data corresponds to central rapidity region, any difference from the analysis of Srivastava et al [7] is not expected.

In the PT scenario it will be assumed that after the collision a baryon free QGP is formed at the initial time τ_i and at temperature T_i . It expands longitudinally and cools till the critical temperature T_c is reached and the fluid enters into the mixed phase. The matter remains in the mixed phase until all the QGP matter is converted adiabatically into the hadronic matter. The hadronic matter then cools further till the freeze-out temperature T_f is reached at time τ_f . In the NPT scenario's, it will be assumed that after the collision again a baryon free hot hadronic gas *ideal* or *viscous* is formed at initial time τ_i and at temperature T_i . It also expands longitudinally and cools till the freeze-out temperature T_f is reached. As in ref. [7], the hot hadronic matter will be considered to be composed of $\pi, \rho, \omega, \eta, \eta', \phi, K$ and K^* as well as axial vector mesons A_1 . As will be shown below, hadron gas with such a limited number of resonances will require a very large initial temperature to reproduce the experimental multiplicity and it is difficult to believe in their existence. As in ref. [7] we have neglected transverse expansion. At SPS energy, transverse expansions are not much [13]. Two pion correlation studies also indicate that if at all there is transverse expansion, it is small [14]. Srivastava and Sinha [15] also showed that at SPS energy, direct photon production including transverse expansion differ marginally from the yield obtained assuming only longitudinal expansion. We thus feel it is justified to neglect transverse expansion.

The paper is organised as follows: in section 2, we describe the frozen motion model. Dilepton yields are obtained in section 3. The summary and conclusions are given in section 4.

II. FROZEN MOTION MODEL

In the Bjorken hydrodynamics [8], the fluid undergoes boost-invariant longitudinal expansion. While boost-invariance is a good approximation in central rapidity region, it certainly fails at forward rapidity region. Frozen motion model [6] is the minimal extension of the Bjorken hydrodynamics. It is assumed that at each rapidity, one can consider a small region where the fluid temperature, energy density etc. do not vary appreciably, and Bjorken hydrodynamics can be applied locally. This is the so called local fluid approximation [16] and reminiscent of local density approximation in Nuclear structure calculations [17]. This approximation will hold true for dileptons with large transverse mass [18]. Space-time integrated dilepton yield from a longitudinally expanding system can be written as [19],

$$\frac{dN}{dM^2 dy d^2 p_T} \approx \int d^4 x \exp[-M_T \cosh(\Theta - y)/T] \quad (1)$$

In the above, M_T is the transverse mass of the lepton pairs, T is the temperature and Θ is the fluid rapidity. For large values of the transverse mass compared to the temperature, we can write [20],

$$\exp[-M_T \cosh(\Theta - y)/T] \approx \exp[-M_T/T] \exp[-M_T(\Theta - y)^2/2T] \quad (2)$$

Thus, it is seen that if the fluid rapidity density distribution is a Gaussian $\approx \exp(-\Theta^2/2\sigma^2)$ and $\sigma \gg (T/M_T)^{1/2}$, variation of temperature etc. over the relevant range of the fluid rapidity can be ignored [18]. In terms of invariant mass (M) of the lepton pairs, more stringent condition for the validity of local fluid approximation can be written as,

$$M \gg T/\sigma^2 \quad (3)$$

As will be shown below, at SPS energy for S+W collisions, $\sigma \sim 1.51$. In the QGP scenario, fluid temperature ~ 200 MeV is expected. The local fluid approximation is then valid for invariant mass $M \gg 0.08$ GeV. In the hadronic gas scenario much higher temperature (300-400 MeV) is expected. The approximation will be good only for invariant mass larger than 0.13-0.18 GeV.

In the frozen motion model [6], it is further assumed that the fluid rapidity is frozen i.e. rapidity of any matter element remain unchanged during the evolution. The freeze-out time of the fluid element then can be obtained from experimental pion rapidity distribution. Consider a fluid element in a rapidity interval $\Delta\eta_i$ around the rapidity η_i . For dileptons with large transverse mass, as indicated above, energy density $\varepsilon(\tau, \eta_i)$ can be *assumed* to vary negligibly with the rapidity in that interval such that: $\varepsilon(\tau, \eta_i) \approx \varepsilon_{\eta_i}(\tau)$. The space-time evolution of the ideal/viscous fluid in the rapidity interval will be governed by the energy momentum conservation equation, which for one dimensional similarity flow can be written as [8],

$$\frac{d\varepsilon_{\eta_i}}{d\tau} = -(\varepsilon_{\eta_i} + p_{\eta_i} - \frac{4\lambda_{\eta_i}}{3\tau} - \frac{\zeta_{\eta_i}}{\tau})/\tau \quad (4)$$

where ε_{η_i} and p_{η_i} are the energy density and pressure of the fluid in the rapidity interval $\Delta\eta_i$ around the rapidity η_i . λ_{η_i} and ζ_{η_i} are the shear viscosity and the bulk viscosity coefficients respectively. To make the notation simpler, in

the following the subscript η_i will be suppressed with the understanding that, unless otherwise stated, the kinematical variables corresponds to a rapidity interval $\Delta\eta_i$ around the rapidity η_i . In the scenario where the QGP or the hot ideal hadron gas is formed as the initial state $\lambda = \zeta = 0$, while in the scenario where viscous hadron gas is formed, the viscosity coefficients will have definite values which we take from ref. [11,21,22].

$$\lambda \simeq T/\sigma_\eta \quad (5a)$$

$$\zeta = \frac{2}{3}\eta \quad (5b)$$

where, σ_η is the transport cross section for which a value of 10 mb is used [11].

Eq.4 can be solved at each fluid rapidity given the equation of state and one boundary condition. We have used the standard bag model equation of state $p_q = g_q\pi^2/90T^4 - B$ with $g_q=47.5$ for the QGP phase. For the hadronic phase, the pion gas equation of state $p_h = g_h\pi^2/90T^4$ with $g_h=6.8$ was used [7]. The mixed phase was described by the Maxwell construct $p_q(T_c) = p_h(T_c)$, which also gives the bag constant B.

In the local fluid approximation, initial temperature of the fluid depends on the fluid rapidity $T_i = T_i(\eta)$ [16]. For the ideal QGP/hadronic fluids for a given initial time τ_i , $T_i(\eta)$ can be obtained by equating the entropy density with the experimental pion multiplicity at that rapidity [23].

$$T_i^3(\eta)\tau_i = \frac{1}{\pi R_A^2} \frac{c}{4a_{q,h}} \left(\frac{dN}{dy} \right)_{y=\eta_i} \quad (b=0) \quad (6)$$

where $c = 2\pi^4/45\zeta(3)$, $a_{q,h} = g_{q,h}\pi^2/90$ and $b=0$ corresponds to central collisions. R_A is the transverse radius of the system. Eq.6 thus maps the experimental rapidity distribution into a temperature distribution. For viscous hadronic fluid, eq.6 can not be used to obtain $T_i(\eta)$ as entropy is generated in the flow. However, the pion multiplicity can be equated with the final entropy density to obtain the freeze-out time ($\tau_f(\eta)$) for a given freeze-out temperature (T_f) [11],

$$T_f^3\tau_f(\eta) = \frac{1}{\pi R_A^2} \frac{c}{4a_h} \left(\frac{dN}{dy} \right)_{y=\eta_i} \quad (b=0) \quad (7)$$

and the evolution equation can be solved with $(T_f, \tau_f(\eta))$ to obtain the initial temperature $T_i(\eta)$. We note that eq.7 is obtained if the fluid flow is convoluted with the thermal distribution and is valid for both the ideal and the viscous flow.

Now the information on $dN/d\eta$ vs η for the HELIOS-3 experiment is not available. We then proceed with the assumption that the $dN/d\eta$ vs η for S+W and that for S+Au are the same. In fig. 1, we have shown the pseudorapidity distribution for the charged particles as obtained by the WA80 collaboration for central S+Au collisions [24]. Also shown is a fit to the data by a Gaussian,

$$dN_{ch}/d\eta = \alpha \exp(\eta - \bar{\eta})^2/2\sigma^2) \quad (8)$$

with, $\alpha = 161.48$, $\bar{\eta}=2.63$ and $\sigma=1.51$.

Neglecting the difference between the rapidity and the pseudorapidity distributions (for large y they are nearly same), the rapidity distribution $dN/d\eta$ for S+W collisions in the HELIOS-3 experiments is obtained by multiplying the above by 1.5 (we are assuming that for every charged pair there is a neutral one). We note that we may be overestimating $dN/d\eta$ for S+W as we are neglecting the mass difference between Au and W ions. Thus we may be overestimating the freeze-out time and also the initial temperature of the fluid. In fig.2, the initial temperature of the fluid, at the (canonical) initial time $\tau_i=1$ fm, in the rapidity range 3.7-5.2, which corresponds to the HELIOS-3 experiment is shown. The critical and the freeze-out temperatures were taken as 160 MeV and 140 MeV. For the fluid elements with $y > 4.2$, dN/dy is such that, in the PT scenario, the fluid can not exist in a *pure* QGP phase. *They were assumed to be formed in the mixed phase, with appropriate QGP and hadron gas fraction.* Thus in the present discussion, in the phase transition scenario, the fluid is essentially formed in a mixed phase [6]. In this scenario, variation of T_i over the rapidity range is quite small (176 -160 MeV). Much larger T_i is obtained if the initial state is the hadron gas. Thus if *ideal* hadron gas is formed T_i varies between 337 MeV (at $\eta=3.7$) to 226 MeV(at $\eta=5.2$). Initial temperature is reduced if the hadron gas is *viscous*. T_i then varies between 291-161 MeV. This is because entropy is generated in a viscous flow. In fig.3, we have shown the corresponding hadronic density. For the ideal hadron gas, initial density varies between 4.2-1.2 hadrons/ fm^3 in the rapidity range considered. It is difficult to believe in the existence of hadronic gas with density as large as 4.2 hadron/ fm^3 . For example the close pack density

of hadronic gas composed *solely* of pions is ~ 2.6 pions/ fm^3 . With resonances, it will still be lower. It is thus difficult to believe that hadronic gas comprising of $\pi, \rho, \omega, \eta, \eta', \phi, K, K^*$ and A_1 mesons can exist at a temperature of 330 MeV and with a density of 4 hadrons/ fm^3 . The hadrons will overlap completely and their identity will be lost. However, we still consider it as our intention was to compare frozen motion model with the calculations of Srivastava et al [7] where such a gas was considered. The situation is better for the viscous hadron gas. Hadron density is considerably lower, it varies from 2.7-0.4 hadrons/ fm^3 their existence can be argued.

III. DILEPTON EMISSION RATE

The dilepton emission rate from the hot hadronic gas have been computed by Srivastava et al [25]. All the possible reaction channels including the A_1 resonance were considered. The details can be found in ref. [25,26]. For lepton pairs of invariant mass (M) and transverse mass $M_T = \sqrt{M^2 + p_T^2}$ where p_T is the transverse momentum, the production rate can be written as,

$$\frac{dN}{dx^4 dM^2 dM_T} = \frac{\sigma_{eff}(M)}{2(2\pi)^4} M^2 M_T K_0(M/T) \quad (9)$$

with

$$\sigma_{eff}(M) = \frac{4\pi}{3} \frac{\alpha^2}{M^2} \left[1 + \frac{2m_l^2}{M^2}\right] \left[1 - \frac{4m_l^2}{M^2}\right]^{1/2} \left[1 - \frac{4m_\pi^2}{M^2}\right] F_{eff} \quad (10)$$

where F_{eff} is the effective form factor [27]. The corresponding result for the emission from the QGP is obtained from the above by replacing F_{eff} by $24/3$ and m_π by m_q [7]. In writing eq.9, we have not distinguished between the particle and fluid rapidities [6].

Invariant mass distribution of lepton pairs is obtained by convoluting the above equation over the space-time history of the system. In the HELIOS-3 experiment, pseudorapidity rather than rapidity was measured. The above rapidity distribution is then converted into the pseudorapidity distribution using the usual procedure. For comparison with experiment we require the acceptance of dileptons in certain rapidity window $[y_1, y_2]$. For dileptons with invariant mass M and rapidity y , the acceptance is calculated as [6],

$$A(y, M) = \int_{\max[0, \tanh(y-y_1)]}^{\min[1, \tanh(y_2-y)]} f(\cos\theta) d\cos\theta \quad (11)$$

where $f(x) = 1 + x^2$ is the process dependent angular distribution and is normalised within $x=0,1$.

The invariant mass distribution of lepton pairs in the pseudorapidity interval $[\eta_1, \eta_2]$ is then obtained as,

$$\begin{aligned} \frac{dN}{dM} &= \pi R^2 \frac{\sigma_{eff}(M)}{(2\pi)^4} M^3 \int_{\eta_1}^{\eta_2} d\eta \int_{\tau_i}^{\tau_f(\eta)} \tau d\tau \\ &\times \int_{P_{Tmin}}^{\infty} dP_T A(y, M) \sqrt{1 - \frac{M^2}{M_T^2 \cosh^2(y)}} P_T K_0(M_T/T) \end{aligned} \quad (12)$$

In fig.4, we have shown the result of our calculation in the PT scenario (the solid line). It is compared with the calculation of Srivastava et al [7] which was obtained following the treatment of Sinyukov et al [9]. Dilepton numbers predicted in the frozen motion model is nearly a factor of 10 lower than that obtained in the treatment of Sinyukov et al [9]. The difference between the two model calculations can be understood. In the treatment of Sinyukov et al [9] the fluid and the particle rapidities are distinguished. For the HELIOS-3 data Srivastava et al [7] limited the fluid rapidity between $[-1.7, 1.7]$ and used the Bjorken hydrodynamics with $dN/dy=225$. They obtained the initial temperature as $T_i = 204$ MeV which remain fixed throughout the fluid rapidity region. In the frozen motion model, the initial temperature of the fluid being is a function of the rapidity and was never so large in the rapidity range covered by the HELIOS-3 collaboration. Indeed as described earlier, in some rapidity ranges, the fluid is in mixed phase, rather than in pure QGP phase. Thus on the average, the initial fluid temperature is much less in the present model than in the model of Srivastava et al [7]. Consequently, production of dileptons is less in the present model than in their model.

In fig.5, the same results in the NPT scenario is shown. As in the PT scenario, here again, we find that the treatment of Sinyukov et al [9] results in more dileptons (by a factor of 10) than in the frozen motion model. As

before, the difference can be attributed to the larger initial temperature of the fluid in Sinyukov treatment than in the frozen motion model. Thus both in the PT and the NPT scenario, frozen motion model predicts lesser dileptons than in the model of Sinyukov et al [9].

In fig. 6, we have compared the invariant mass distribution of lepton pairs as obtained by the HELIOS-3 collaboration [1] with the dilepton yields obtained in the frozen motion model. The solid line corresponds to the phase transition scenario, when the QGP is formed in the initial state. The long-dashed line corresponds to the no phase transition scenario with the ideal hadron gas formation as the initial state. We have also shown the dilepton yield obtained in the scenario when viscous hadronic gas is formed in the initial state (the dashed line).

All the three scenarios underpredict the low mass ($M < 0.8$ GeV) dilepton pairs. As mentioned earlier local fluid approximation is a good approximation only for high mass dilepton pairs. For low mass dilepton pairs, the model predictions may not be reliable. The low mass dileptons are essentially from the freeze-out surface and it is possible to improve the fit of low mass dileptons by increasing the freeze-out temperature. However, we desist from such parameter fitting. As now well known, the discrepancy may be more due to neglect of modification of ρ mass and width in hot and dense hadronic medium [28]. However, since the present model is not reliable for low mass dileptons, we will not discuss this issue further.

In the invariant mass range of 1-2 GeV, the data are underpredicted in all the three scenarios. Thus in all the three scenarios the frozen motion model do not produce requisite number of lepton pairs in the invariant mass range 1-2 GeV, indicating excess dileptons in the experiment. To have quantitative idea about the excess dileptons, we define a ratio r as,

$$r = \frac{\text{Integral contents of data histogram}}{\text{Integral content of theory}} \quad (13)$$

The ratio r was calculated in the invariant mass range 1-2 GeV and found to be 10.0, 2.2 and 4.2 for the initial QGP, ideal hadronic gas and the viscous hadronic gas respectively. Dilepton excess is minimum in the NPT scenario with the ideal hadron gas formation and maximum in the PT scenario.

The PT scenario also underpredict the large invariant mass ($M > 2$ GeV) data. They are underpredicted by a factor of 40 or so. On the otherhand the NPT scenario with the ideal hadronic gas overpredict the large invariant mass data by a factor of 5. Very good description of the large mass data is obtained in the NPT scenario with the viscous hadronic gas. As the large mass dileptons are essentially from the initial state of the produced fireball, it seems that it is best described by the hot viscous hadronic gas.

Present analysis indicate that in the frozen motion model, the PT scenario do not describe HELIOS-3 data. The NPT scenario also do not fits the data however overall description is better than in the PT scenario. This is exactly opposite to the results obtained by Srivastava et al [7] following the treatment of Sinyukov et al [9]. Of the two NPT scenarios considered e.g. ideal and viscous hadronic gas, the ideal hadronic gas give better description to the data compared to the viscous hadronic gas, though the high mass dileptons are overpredicted by a factor of 5 or so. However, as discussed earlier, in the ideal hadronic gas scenario, the initial temperature of the fluid is very large (> 300 MeV) and it is difficult to conceive existence of such a gas. Thus though the hadronic gas gives a better description to the data, it can not be considered seriously. The viscous hadronic gas on the otherhand require much less initial temperature and can be believed to be in existence.

One of the limitation of the present model is the neglect of baryons. While the assumption of baryon free fireball may be quite accurate in the central rapidity region, in the forward rapidity region it is not so. As the HELIOS-3 data lies in the forward rapidity region, it is essential to include baryons. Inclusion of baryons will introduce two complimentary effects. The initial temperature of the fireball will be reduced, as a result of which dilepton yield will be decreased. On the otherhand dilepton yield will be increased as the number of reaction channels are increased. It is possible that these two complimentary effects cancels each other and the present results is not changed significantly [7].

IV. CONCLUSION

To summarise, we have analysed the HELIOS-3 dilepton data in the frozen motion model. Earlier Srivastava et al [7] analysed this data following the treatment of Sinyukov et al [9]. They found that formation of QGP as the initial state fits the data. If on the otherhand, hadronic gas is formed, the data could not be fitted. In the frozen motion model, we obtain entirely different results. Both the PT and NPT scenario could not fit the data satisfactorily. There is excess dileptons in the intermediate mass range. Interestingly, we also find that the NPT scenario gives the better description to the data compared to the PT scenario. Thus if one can believe in the existence of hot hadronic gas at a temperature in excess of 300 MeV, reasonable description to the data can be obtained. However, it is difficult

to believe that hadrons retain their identity at such large temperature. The other NPT scenario with the viscous hadronic gas, do not require very large initial temperature and gives very good description of large mass dileptons. It can be an alternative to the ideal hadronic gas that is generally considered in literature.

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FIG. 1. The rapidity distribution of the charged particle in 200 A GeV S+Au collisions as obtained by the WA80 collaboration. The solid line is a Gaussian fit to the data.

FIG. 2. Initial temperatures (T_i) of the QGP, ideal hadron gas and the viscous hadron gas as a function of rapidity.

FIG. 3. Initial density (ρ_i) of the ideal and the viscous hadronic gas as a function of rapidity.

FIG. 4. The invariant mass distribution of dilepton pairs in the Phase transition scenario. The solid line corresponds to the frozen motion model. The dotted lines are results from ref. [7]. Cuts corresponding to the HELIOS-3 experiments are incorporated.

FIG. 5. The invariant mass distribution of dilepton pairs in the no Phase transition scenario. The solid line corresponds to the frozen motion model. The dotted lines are results from ref. [7]. Cuts corresponding to the HELIOS-3 experiments are incorporated.

FIG. 6. The invariant mass distribution of dilepton pairs as obtained by the HELIOS-3 collaboration. The lines corresponds to initial QGP, ideal hadron gas and viscous hadron gas.











